Quantification of resilience improvements for critical facilities through advanced technologies

Quantification of Resilience Improvements for Critical Facilities through Advanced Technologies

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ABSTRACT: A relevant number of critical facilities, such as hospitals, schools and city halls, experienced extensive damage that resulted in loss of their functionality, and consequently huge economic losses and slow restoration processes after earthquakes. In some communities not well organized, the recovery process can last several years and the community or the system is never brought back to the initial functionality. The awareness that damage can not be avoided has increased the attention on designing buildings that are both safe and resilient, however it is often assumed that such design can increase costs to unacceptable levels. The paper compares life-cycle costs and resilience of respectively a hospital and a school which have been retrofitted using both a moment resisting frame system and a base isolated system. Performance-based earthquake evaluation tools are used to estimate the total cost of ownership, including expenses associated with initial construction, damage repair, loss of functionality and resilience. Numerical analyses have shown that resilience of both schools and hospitals can be improved by using a seismic isolation system that will also reduce life-cycle costs and downtime with respect to a conventional fixed-based design.

1. INTRODUCTION

Healthcare facilities and schools represent a substantial hazard to human life in the event of failure (occupancy category III, per ICC IBC, 2012). Therefore, they are designed following more stringent design requirements then buildings with residential and commercial occupancy. In the recent large earthquakes in Chile, New Zealand, and Japan, healthcare facilities and schools were generally safe. However, there are evidences of healthcare and school closures due to extensive structural and nonstructural damage that resulted in the loss of their function (Miranda et al., 2012). As a result, increased attention is being placed on strategies to design facilities that are both safe and damage resistant. It is often presumed that such an approach increases costs to an unacceptable level. However, the cost-effectiveness of alternative design choices can be assessed using performance-based earthquake evaluation (PBEE) methods (Miranda, 2003) that quantify expected future costs associated with damage repair, loss of functionality, casualties, and so on. This paper presents results of a study that compares the repair times and resilience indices considering two designs for a three-story steel building: high performance special moment resisting frame (HP-SMRF) and damage resistant base-isolated intermediate moment resisting frame (BI-IMRF). Both system's designs comply with the occupancy category III (ICC IBC, 2012), allowing the building to serve either as a healthcare facility or as a school. To aid understanding of the relative performance of these two systems considering the two occupancy types, key engineering demand parameters (i.e., median values of maximum and residual story drifts and floor accelerations), repair costs, and repair times and resilience indices are compared at five hazard levels. These results are then used to estimate the resilience of the two systems.

2. DESCRIPTION OF THE SCHOOL AND HOSPITAL BUILDING

The study considered a three-story steel building located in Oakland, California. The basic building plan dimensions are 120 ft (36.5 m) by 180 ft (54.9 m) with a bay spacing of 30 ft (9.1 m) in each direction (Figure 1).

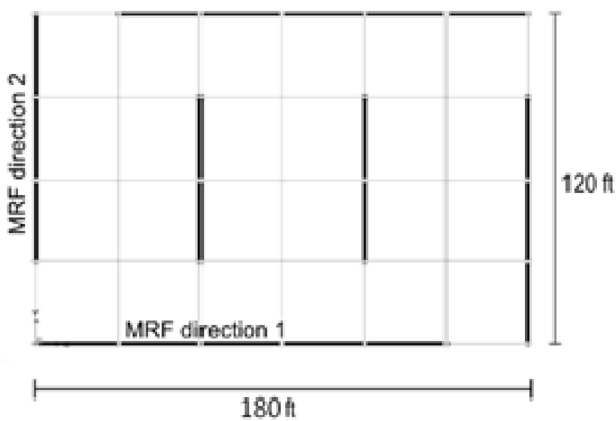


Figure 1: Building plan (Mayencourt, 2013).

The building is located on relatively stiff soil (site class C/D with reference shear wave velocity = 180 to 360 m/s). Code spectral accelerations were selected to be Ss = 2.2g for short periods and S_1 = 0.74g at a period of 1 sec. The designs of the two considered systems, fixed-base and base-isolated moment resisting frames, are consistent with what might be used by many engineers and are compliant with the code standards for design according to the Equivalent Lateral Force Method (ASCE, 2010). The HP-SMRF was designed with a force reduction factor (R/I_e) of 6.4 (8/1.25), an interstory drift limit of 1.0% (more stringent than 2% required by code – ASCE, 2010), and utilized prequalified WUF-W beam-to-column connections (AISC, 2005). Such design resulted in fundamental period of the fixed-base system of 0.67 sec. Compared to the HP-SMRF, the BI-IMRF was designed utilizing lower R/I_e factor (1.69=(3/8)x(4.5/1)) and the same drift limit (1.0%). The IMRF uses simpler connection details and does not require a strong column-weak girder design approach. The isolation system is designed to have a maximum displacement of 30 in. under the maximum capable earthquake (MCE) event. It utilizes triple friction pendulum bearings (TFPB) with the friction coefficients of the four sliding surfaces of 0.01, 0.01, 0.03, and 0.06, and the effective pendulum lengths of 20, 122, and 122 in (Figure 2). Under the MCE event, this bearing has the effective period of 4.35 sec and the effective damping of 15.1% (Table 1). More details on designs of these two systems can be found in Mayencourt (2013) and Terzic *et al*. (2014a).

Table 1: Parameters of the Isolation system.

	DBE	***MCE***
Effective period	*3.95 sec*	*4.35 sec*
Effective damping	*22.9 %*	*15.1 %*
Isolator displacement	*16.1 in.*	*30 in.*

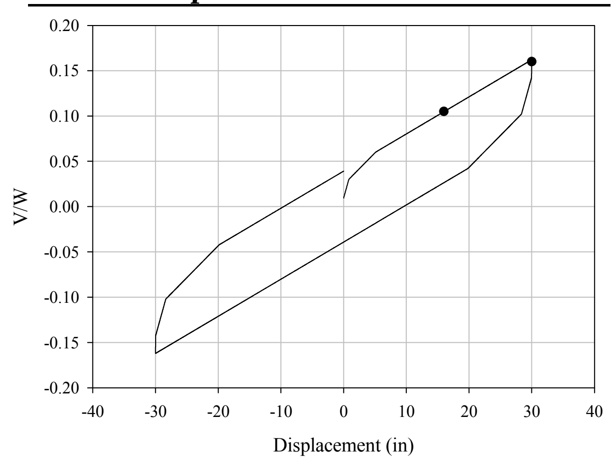


Figure 2: Hysteretic behavior (normalized force vs horizontal displacement) for the triple friction pendulum bearing.

3. SELECTION OF GROUND MOTION

The set of ground motions used in the analysis were selected to match the uniform hazard spectrum (UHS) (USGS, 2013) and associated causal events for the Oakland site. Forty three-component ground motion records were selected to represent the ground motion hazard at each of three hazard levels: 2%, 10%, and 50% probabilities of exceedence in 50 years. More information on these motions can be found in Baker *et al.* (2011). To better characterize the seismic hazard at the site, two additional sets of records representative of hazard levels at 5% and 20% probabilities of exceedence are also used in the analysis. Each of the two additional sets of ground motions had 25 three-component ground motion records, derived following the selection criteria given in Baker *et al.* (2011). Figure 3 compares the UHS with the median pseudo-acceleration response spectra for the selected ground motions at a considered hazard level.

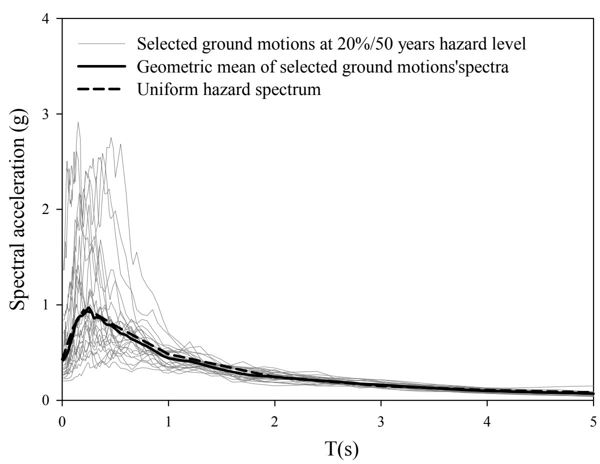


Figure 3: Uniform hazard spectrum at the 20% in 50 years hazard level and response spectra of the selected ground motions.

4. DESCRIPTION OF THE NUMERICAL MODEL

To simplify the analysis for this study, time history analyses were performed on appropriately modeled two-dimensional (2D) frames utilizing OpenSees (McKenna and Fenves, 2004). This simplification is valid as the lateral load resisting frames are located only on the perimeter of the building and do not have common elements. Gravity-load-only type connections were used elsewhere in the structure. Details of numerical models and modelling assumptions are described in Terzic *at el.* (2014a).

In summary the main assumptions in the model are: (i) floor slabs were assumed to be axially inextensible, (ii) all elements of the two moment resisting frames were modeled utilizing force-based beam-column elements of OpenSees, (iii) isolators were modeled with zero-length elements (horizontal springs), one beneath each column of the structural frame, and tri-linear uniaxial material representative of a hysteretic behaviour of triple pendulum friction bearing, (iv) P-Δ effects from the gravity columns were accounted for by using single leaning column (Figure 4), (v) the effects of large deformations of beam and column elements were accounted for utilizing P-Δ nonlinear geometric transformation, (vi) damping was assigned to the frames using Rayleigh damping model and the damping ratio of 3%, (vii) the frames were subjected to horizontal and vertical components of ground motions.

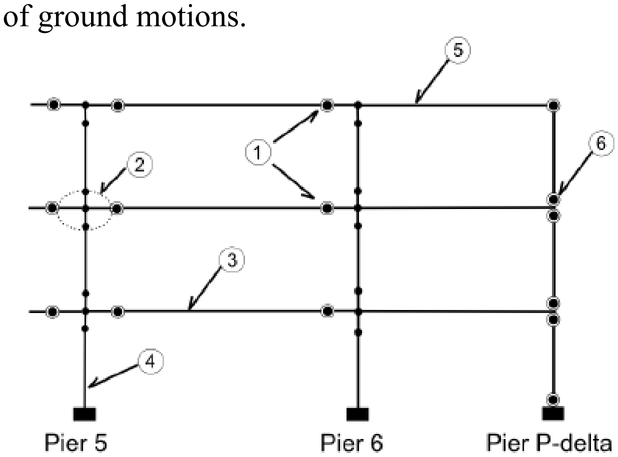


Figure 4: Structural scheme of a generic bay and the P-delta leaning column. (1) Reduced Beam Section connections, (2) Panel zone, (3) Elastic beam-column elements, (4) Columns, (5) Rigid truss, (6) P-delta floor connections (Mayencourt, 2013).

5. RESULTS

The severity of damage of structural and nonstructural components associated with the engineering demand parameters (EDP) such as the story drifts, the floor accelerations, and the residual drifts, can be quantitatively assessed using fragility relations from FEMA P-58 (FEMA, 2012). The base-isolated moment frame substantially reduces accelerations and drifts compared to the fixed-base frame (Figure 5). While the effectiveness of the isolation system in reducing the story drifts increases with the increase of intensity of ground shaking (from 20% to 62% with an average of 49%), the reduction of acceleration is high at all hazard levels (from 84% to 90% with an average of 88%).

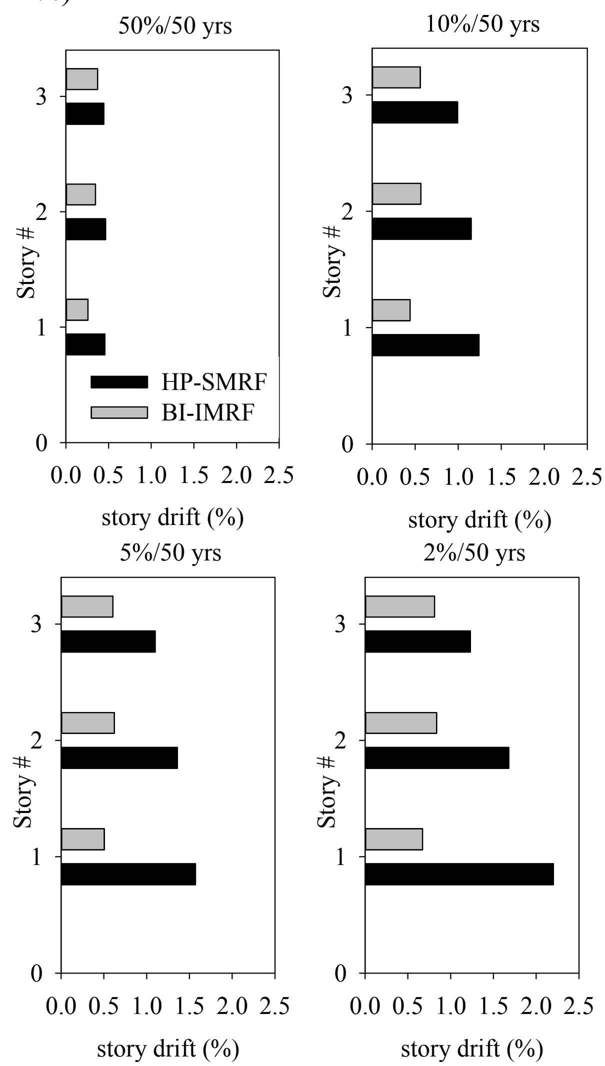


Figure 5: Median story drifts of the HP-SMRF and the BI-IMRF on TFPBs for four of the five hazard levels selected - Hospital.

The BI-IMRF, with the uniform acceleration profile over the height of the building and the peak median value reaching 0.22g at the 2% in 50-year hazard level, most likely will not trigger any damage of the acceleration sensitive components (e.g., ceiling, MEP, contents). At the 50% in 50-year hazard level, the HP-SMRF develops maximum median drift of 0.46%, 20% larger than maximum median drift of the BI-IMRF of 0.37% (Figure 5). Because both moment frames are expected to yield at drift ratios slightly larger than 1%, elastic structural behavior is anticipated at this hazard level. The damage to interior partitions is expected for both the HP-SMRF and BI-IMRF system, since the median drift associated with initiation of damage to partition walls commonly used in healthcare facilities and schools is 0.21% (FEMA, 2012). Median horizontal accelerations in the HP-SMRF range from 0.26*g* to 0.67*g* over the height of the building (not shown), likely triggering damage to piping, electronic and medical equipment in the upper levels (FEMA, 2012). Compared to the BI-IMRF, the fixed-base HP-SMRF had about 2 times larger drift ratio at every level, with the peak median value reaching 0.84%. This would likely result in a greater damage to partition walls and initiation of damage to stairs (that initiates at drift of 0.5%, per FEMA 2012). At this hazard level, damage to structural elements is not anticipated. At the 10% in 50-year hazard level, Figure 5 shows even greater differences in story drift demands between the two systems. The fixed-base HP-SMRF had the peak median drift ratio of 1.24%, which suggests initiation of yielding of the system and probable extensive damage to wall partitions and moderate damage to stairs. The BI-IMRF, with the peak median drift ratios of 0.62% (5% in 50 years) and 0.83% (2% in 50 years) is anticipated to remain elastic with slight non-structural damage.

5.1. Loss analysis

Two loss metrics used to estimate effectiveness of isolation system in reducing the total financial losses are: (1) financial losses associated with the cost required to implement repairs and (2) repair time. The computer software Performance Assessment Calculation

Tool (PACT) (ATC, 2012) is used to calculate repair costs and repair times for the two systems (fixed-base and base-isolated moment frames) and two occupancy types (healthcare and school), at each of five considered hazard levels.

In PACT, each building component and content is associated with a fragility curve that correlates EDPs to the probability of that item reaching a particular damage state.

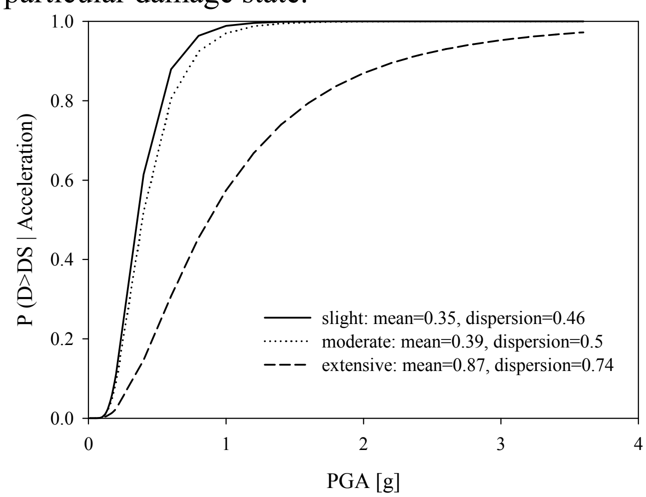
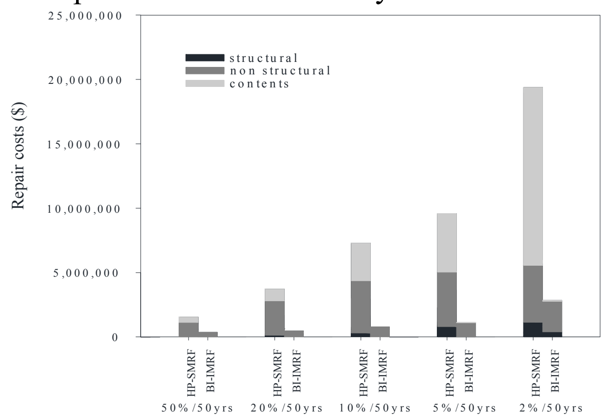
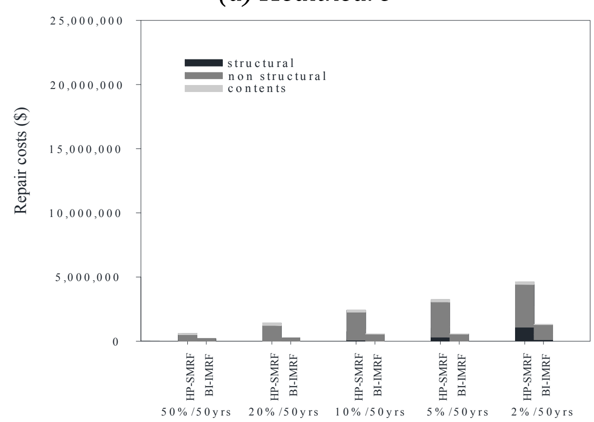


Figure 6: Fragility curve for medical equipment (Yao and Tu, 2012).

The component's damage is then related to a loss (e.g., repair cost or repair time) utilizing consequence functions. The total loss at a hazard level is then estimated by integrating losses over all components of a system. To account for the many uncertainties affecting calculation of seismic performance, the *FEMA P-58* methodology uses a Monte Carlo procedure to perform loss calculations (FEMA, 2012). The type and quantities of most non-structural components and contents used in the loss analysis were determined using the normative quantities recommended by *FEMA P-58* (FEMA, 2012). For the healthcare occupancy, the fragility functions for the medical equipment (not available in PACT) are adopted from Yao and Tu (2012). These fragility functions are derived by investigating 41 healthcare buildings in the aftermath of the 1999 Chi-Chi earthquake (Figure 6). The consequence functions, relating damage of medical equipment to the repair cost, are developed based on an estimate that the medical equipment cost is 44% of the total building cost (Taghavi and Miranda 2003). The consequence functions, relating damage of medical equipment to the repair time, were not developed due to unavailability of data.



(a) Healthcare



(b) School

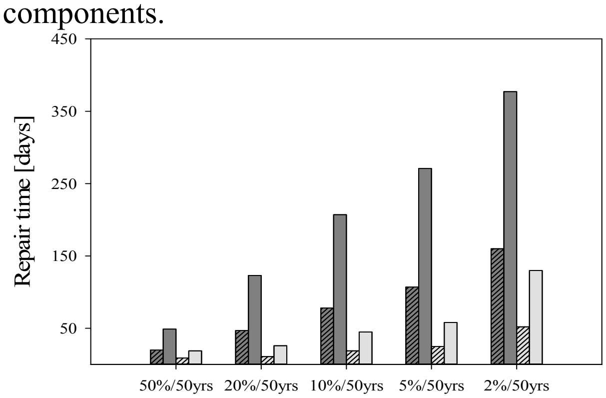
Figure 7: Median repair costs for the HP-SMRF and the BI-IMRF for five hazard levels

Replacement costs for the buildings, which are input for the loss analysis with PACT, are equal to the initial construction cost increased by 20% to include cost allowances for demolition and site clearance (FEMA, 2012). The initial construction costs of the school are estimated to be $17,823,000 for the HP-SMRF and $17,408,000 for the BI-IMRF, the same as if it was a commercial building (Terzic *et al.* 2014a; Ryan *et al.* 2010). The initial construction cost of the healthcare facility was calculated using the metric of $597.7/ sq ft (estimate by M. Phipps per Mayencourt, 2013). Considering the footprint of the three-story building, the initial construction cost of the healthcare is estimated to be $38,730,960, the same for the two considered structural systems.

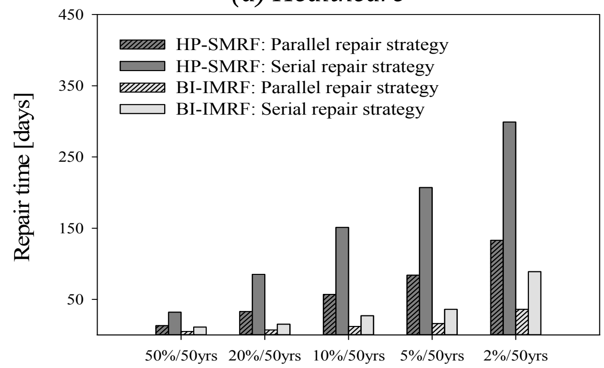
5.1.1. Evaluation of repair costs and repair time

The median repair costs (not shown) for the fixed-base and base-isolated moment frames and for the two occupancy types (healthcare and school) show the effectiveness of base-isolated system in mitigating damage.

Healthcare facility, whose initial cost is double of the school cost, has 3-4 times greater losses than the school if the fixed-base HP-SMRF is utilized, and about 2 times greater losses if the BI-IMRF is utilized. To estimate the resilience of the system and the revenue losses resulting from the business interruption following an earthquake event, business downtime as a function of time needs to be characterized. Business downtime should include the time required to: (1) identify damage, design repairs or upgrades, obtain permits and financing, and to mobilize supplies and manpower; and (2) make the repairs necessary to restart operations. Although business models exist for the commercial occupancy type (e.g., Terzic *et al.* 2014a) such model could not be found for a school or a healthcare facility. To calculate repair time, a number of assumptions are made. It is assumed that supplies and workers are available to permit necessary work. A high density of workers (one worker per 500 ft^2) is used assuming that the building will not be occupied during the repair of damaged building components.



(a) Healthcare



(b) School

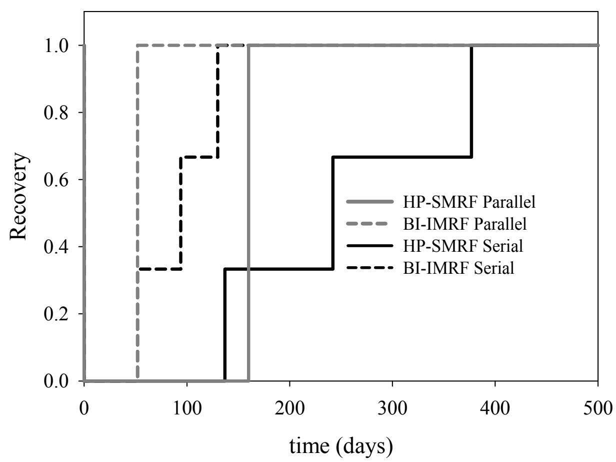
Figure 8: Median repair times for the HP-SMRF and the BI-IMRF for five hazard levels and two occupancy types: (a) healthcare and (b) school, considering two repair strategies, parallel and serial

The repair time is calculated considering two repair schemes: (1) *parallel* scheme that assumes simultaneous repair at all three floors, and (2) *serial* scheme that assumes sequential repair at three floor levels (FEMA, 2012). Both repair schemes assume sequential repair of all damaged components within one floor level. These repair schemes are not optimal but provide a good estimate of the lower and upper bound of the repair time for the chosen density of workers. While the assumptions made may be feasible for the systems with the smaller extent of damage (i.e., isolated system), they may be hard to achieve for the systems with more extensive damage (i.e., the fixed-base system). Therefore, these assumptions are advantageous for the HP-SMRF relative to the base isolated system as they reduce relative benefits of the isolated system. Figure 8 shows the median repair times for the HP-SMRF and the BI-IMRF for five hazard levels, for the school and the healthcare facility, considering two repair strategies, parallel and serial. Base-isolation is again very effective in reducing the repair time, which also implies significantly smaller downtime of the isolated buildings. Upper (serial) and lower (parallel) bounds of the repair times are both several magnitudes smaller for the isolated buildings relative to the fixed-base buildings.

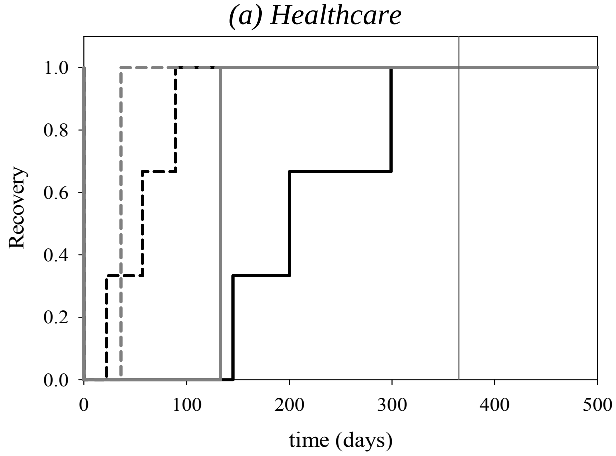
While repair costs were significantly larger for the fixed-base healthcare facility than for the school, their repair times are of the same order of magnitude (Figure 8). If the repair time of the medical equipment was included in the loss analysis, greater difference between repair times of the school and the healthcare facility, and between the fixed-base and the base-isolated healthcare facility would be anticipated.

5.2. Resilience analysis

Resiliency is the ability of a system to re-establish its function following a hazard event. The level of resiliency is measured by integrating the recovery function of the system within a certain period of time (Cimellaro et al, 2010a, b). To quantify the resiliency of the considered building, recovery function needs to be known.



(a) Healthcare



(b) School

Figure 9: Recovery functions of the HP-SMRF and the BI-IMRF considering hospital and school occupancy at 2% in 50-year hazard level

For the considered systems, it can be easily observed that the base-isolated buildings are more resilient than the fixed-base buildings as they have significantly smaller repair times and will therefore recover faster. However, to better quantify resilience an attempt is made towards developing resilience functions considering school occupancy and a very rare earthquake with a 2% probability of exceedence in 50 years. For this hazard level, it is assumed that both the fixed-base and the base-isolated system incur enough damage to trigger buildings closure. The probable lower and upper bounds for the recovery and therefore resiliency are established based on the lower (parallel scheme) and upper (serial scheme) bounds of repair times. Considering the recovery time of 365 days, resiliency factor for the fixed-base school is between 0.41 and 0.63, while it is higher for the base-isolated building between 0.85 and 0.9. More details can be found in Moretti et al., (2014).

6. CONCLUDING REMARKS

The base-isolated system provide significant median damage savings and repair time reduction compared to the fixed-base system for critical facilities such as schools and hospitals. This stems from the substantial reduction in accelerations, drifts, and residual drifts when isolated system is utilized at the base of the building. In the case study located in Oakland, for the healthcare occupancy, the reduction in repair cost is between 76% and 88%, while for the school it ranges from 66% to 82%. Such reduction in cost of damage repairs of base-isolated systems comes primarily from preventing damage of the expensive equipment and structural components, and from minimizing the damage of non-structural components. Repair times are 3-6 times smaller for the isolated buildings relative to the fixed-base buildings. For the design basis earthquake (10%probability of exceedence in 50 years) and healthcare occupancy, the repair time of the fixed-base building is expected to be in the range of 78 and 207 days, while it is in the range of 19 and 45 days for the base-isolated building. Such reduction in repair time implies significantly smaller downtime and higher resilience of the base-isolated buildings. The work presented here is indicative of the effectiveness of the base isolation in mitigating damage and associated losses, while increasing resilience of the systems considered.

7. ACKNOWLEDGMENTS

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